Sustainable Cities and Society 40 (2018) 233–243

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Implementation of green roof technology in residential buildings and neighborhoods of Cyprus

Isidoros Ziogou, Apostolos Michopoulos*, Vasiliki Voulgari, Theodoros Zachariadis

Energy and Environmental Economics and Policy Group, Department of Environmental Science and Technology, Cyprus University of Technology, P.O. Box: 50329, 3603, Limassol, Cyprus

A R T I C L E I N F O

Keywords:
Green roof
Single-family house
Multi-family house
Neighborhood scale
Sensitivity analysis
Urban heat island mitigation

A B S T R A C T

Green roofs are considered as an appropriate nature-based measure to increase the environmental resilience of cities. This paper examines this technological solution applied to typical urban residential buildings in the Mediterranean island of Cyprus, with respect to energy, environmental, and economic aspects. The analysis shows a clearly positive energy and environmental contribution of green roofs. Although such an investment does not seem to be cost-effective in residential buildings, sensitivity analysis demonstrates that green roofs become financially favorable compared to flat roof constructions with only modest reductions in their current installation cost. Moreover, green roofs offer environmental benefits that are currently difficult to monetize, which can clearly improve urban resilience to climate change. In order to quantify the impact of green roof installations on the surrounding environment, the analysis was expanded from the individual building perspective to neighborhood scale implementation, using appropriate simulation software to evaluate the contribution of green roofs to urban heat island mitigation. Focusing on the ambient air temperature at the pedestrian level, a noticeable decrease was estimated.

1. Introduction

1.1. Literature review

The ongoing global urbanization trend has an indisputable effect on sustainable development. Contemporary societies are structured in a way that is conducive to the accumulation of people in conurbations. This tendency is becoming stronger over the years (UN, 2015). The rising concentration of dwellers in cities around the world comes with changes in land use, ecosystems and environmental quality (UN, 2015). Continuous growth of the building sector, which directly accounted for a 3% increase in the entire yearly anthropogenic greenhouse gas emissions between 2000 and 2010, along with other energy consuming human activities significantly contributes to climate change (IPCC, 2014). Major complications are not only the increase of cities' ambient temperature, which consequently exacerbates energy consumption patterns, lowers amenity standards and sets impediments to economic performance, but also more intensive and unexpected rainfall events leading to urban flood incidents (IPCC, 2014). In order to protect against the deterioration of citizens' well-being, many techniques can be employed, with green roofs being one of them (Jim, 2017). The following analysis focuses on the energy conservation achieved by green roof technology, since water run-off management is a complicated issue that requires dedicated examination in a separate research.

Green roofs improve the energy performance of buildings because they provide higher thermal inertia, shading and absorption of solar energy by the plants, and evapotranspiration cooling effects (GhaffarianHoseini, & GhaffarianHoseini, 2014). Recent research confirms the favorable contribution of this particular technology to improved energy use patterns. For example, the thermal performance of two tall buildings located in Hong Kong was examined under various weather conditions and building thermal insulation (BTI) scenarios, either by identifying the heat flow entering and exiting the building using a coupled green-building roof system (Jim, 2015), or by measuring air-conditioning energy consumption in situ (Jim, 2014). Both studies conclude that green roofs have positive contribution on the thermal mass enhancement, bring notable reduction in cooling loads, and increase energy savings.

Experimental results have also highlighted the positive effect of green roofs to building energy efficiency. For instance, Pandey, Hindoliya, and Mod (2012) proved that the green roof decreases the design cooling capacity up to 1.25 kW in a regular summer day in Ujjain, India, while Theodosiou, Aravantinos, and Tsikaloudaki (2014) confirmed a temperature reduction under the examined green roof's

* Corresponding author.
E-mail address: a.michopoulos@cut.ac.cy (A. Michopoulos).

https://doi.org/10.1016/j.scs.2018.04.007
Received 22 December 2017; Received in revised form 26 March 2018; Accepted 3 April 2018
Available online 05 April 2018
2210-6707/

bitumen coating close to 25 °C in comparison with an ordinary roof formation and under Mediterranean climatic conditions. Furthermore, case-study approaches were adopted to allow a deeper insight into the thermal behavior of an experimental building in Guangzhou, China (Yang, Wang, Cui, Zhu, & Zhao, 2015), a three-story building in Iran (Refahi & Talkhabi, 2015) and a representative four-story building in Amman, Jordan (Goussous, Siam, & Alzoubi, 2015). All three studies indicated that particularly in hot climates, green roofs are quite advantageous in reducing energy consumption, with energy savings ranging from 6.6% to 17%.

Urban microclimate mitigation by the green roofs is also an important aspect considered by recent studies. For example, Berardi (2016) confirmed the positive effects of green roofs both on building energy needs (i.e. energy demand reduction by 3%) and on pedestrians' thermal comfort (i.e. diurnal air temperature reduction of the order of 0.4 °C at pedestrian level). According to Alcazar, Olivieri, and Neila (2016) the combination of green roofs with greenery at pedestrian level can enhance the benefit on the surrounding microclimate with ambient temperature decline up to 2 °C. In contrast with these findings, Vuckovic, Kiesel, and Mahdavi (2017) claim that green roofs do not seem to significantly affect ambient temperature in the urban canyon, but they might be important for better thermal performance of individual buildings. In any case, local climatic conditions, construction types of green roofs (i.e. intensive, extensive, and semi-intensive systems), and spatial planning are key for the microclimatic efficiency of this retrofit option (Morakinyo, Kalani, Dahanayake, Ng, & Chow, 2017).

1.2. Motivation and aim of the research

Adding to earlier analysis of Ziogou, Michopoulos, Voulgari, and Zachariadis (2017), which focused on buildings of the tertiary sector, this study provides a holistic evaluation of the positive contribution of green roof technology to urban residential conditions of the Mediterranean island of Cyprus. The energy, environmental and economic aspects related to the application of green roofs to a typical two-story single-family building and a typical four-story multi-family one in four major cities (Nicosia, Larnaca, Limassol, and Paphos) are examined. Apart from simulating different types of buildings, this paper includes two aspects that had not been considered in the aforementioned study. Firstly, a sensitivity analysis was conducted in an effort to investigate the impact of different monetary variables on the economic evaluation of this nature-based solution and explore the potential of turning it into a more enticing investment. Moreover, the scope of the research is expanded from the individual building perspective to a characteristic neighborhood scale implementation in order to assess the impact of green roofs on the Urban Heat Island (UHI) mitigation.

2. Description of the typical residential buildings and climate characteristics of the study area

2.1. Description of the typical building envelopes

Two characteristic types of residential buildings commonly found nationwide (CYSTAT, 2015) are examined. The first one refers to a freestanding two-story single-family building (Fig. 1) of an entire area of 204 m^2 whose ground floor plan consists of the sitting and dining room, the kitchen and a studying area and its first floor, internally connected with the ground floor by a stairway, comprises a sitting area and three bedrooms. The windows occupy around 15% of the whole façade surface, with 70% placed on the southern and 22% on the northern part of the building.

The second one refers to a freestanding four-story multi-family building constructed over pilotis and is three-dimensionally depicted in Fig. 2. Each typical floor comprises two independent residences, 113.3 m^2 each, besides the communal staircase area. Each residence includes a sitting room, a kitchen, a studying room and three bedrooms. The windows occupy around 17% of the whole façade surface and their majority (60%) is located on the southern part of the building.

Buildings in Cyprus are mainly reinforced concrete constructions with flat roofs. Regarding the thermal insulation conditions, there are two cases found: a) no thermal insulation is applied (mainly in buildings before 2007); b) extruded polystyrene (XPS) layer is placed on the horizontal and vertical elements of the frame and the masonry (mainly in buildings after 2007) (CYSTAT, 2015). Both insulation typologies are considered in the analysis scenarios, in order to comprehensively examine the existing architectural features of the housing stock in Cyprus. For the first case – uninsulated buildings-, the thermal transmittance (U) values of the horizontal structural components, the vertical external concrete elements, and the external masonry are 3.28, 3.56, and 1.39 $W/(m^2 K)$ respectively. For the second case – insulated buildings-, these values are equal to 0.61, 0.62, and 0.52 $W/(m^2 K)$ respectively. In all cases, windows are equipped with aluminum frame and double glazing whose thermal transmittance values are 2.98 $W/(m^2 K)$ and 2.8 $W/(m^2 K)$, respectively.

The selection of the construction elements in both reference building typologies and construction periods has been fully based on the current and past construction practices of the island, while their thermal transmittance values have been calculated in compliance with the Cypriot legislation regarding the energy performance of buildings (Republic of Cyprus, 2015b). In the framework of this study and in order to examine the common cases in which a green roof can be applied on new or renovated residential plots, we have considered uninsulated and perimetrically insulated buildings with either ordinary or two different green roofs that are described in Section 2.2 below.

2.2. Green roof configuration

Among the two dominant green roof typologies, the extensive and intensive ones, the former has been chosen for the purposes of this study mainly due to its shallow soil layer and consequently minimal static stress to the buildings' load bearing structure, and its confined installation costs and maintenance needs (Vijayaraghavan, 2016). The selected construction materials meet certain qualitative criteria that are important for promoting the sustainability of the proposed green roof formations. For example, for the two selected extensive green roof formations, native Mediterranean plants, i.e. *Helichrysum Orientale* (aromatic xerophyte) and *Sedum Sediforme* (succulent plant), have been chosen to separately form the two vegetation coverings because of their inherent ability to withstand adverse local climatic conditions (Butler, Butler, & Orians, 2012). Furthermore, recycling products, i.e. compost in the soil mixture and rubber crumbs as a drainage layer, have been selected not only for their environmental contribution but also for their advanced physical properties (Hill, Drake, & Sleep, 2016; Pérez et al., 2012). More details regarding the formation of the two proposed alternative rooftop retrofit options are included in Table 1 of Section 3.1 and Ziogou et al. (2017).

2.3. Neighborhood design

The impact of the wider implementation of green roof retrofits on the urban microclimate with respect to local prevailing urban planning conditions was examined using an existing representative neighborhood in Limassol. The selected urban formation, whose three-dimensional geometrical domain is presented in Fig. 3, consists of both multi-family buildings and single-family ones that are grouped into blocks and are separated by asphalt roads. The size of the domain area is 197.5 m × 120.0 m. Both building types found in this area have the same construction characteristics with the typical ones used in our analysis. In addition, the ground formation consisting of asphalt roads, concrete pavements, exposed soil and limited grass coverage has been extracted from the actual urban figure and is represented by the black,

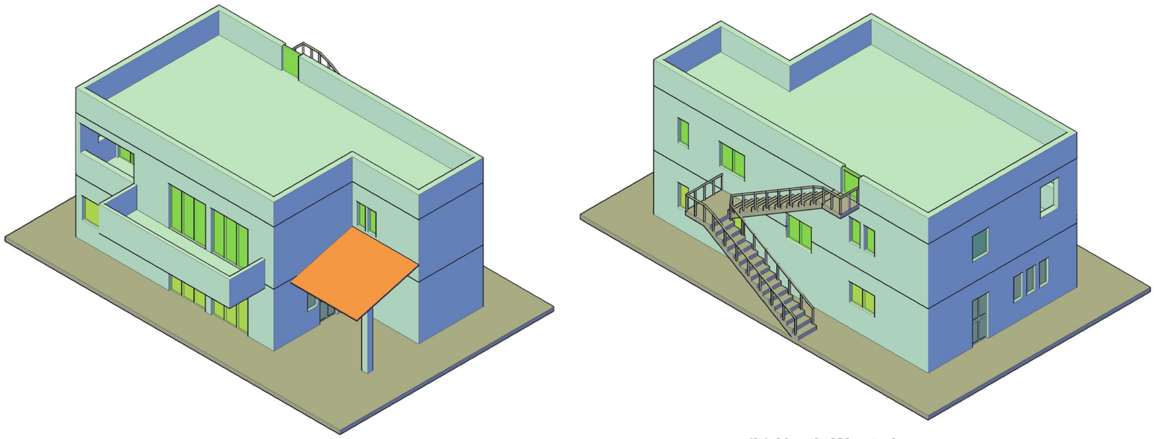

Fig. 1. Panoramic view of the examined single-family building; South-East view *(a)* and North-West view *(b)*.

grey, orange and green colored areas of Fig. 3, respectively.

2.4. Climatic characteristics

The climate of Cyprus (latitude 35° north, longitude 33° east) is characterized by hot dry summers from mid-May to mid-September, and rainy, pretty variable, winters from November to mid-March that are separated by short autumn and spring seasons of swift alteration in weather conditions (Republic of Cyprus Department of Meteorology, 2017). Regarding the examined regions, Nicosia, the capital city of Cyprus, presents the coldest climate of the study area as the heating degree days ($HDD_{20/12}$) are equal to 441 Kdays, according to the METEONORM meteorological database (Meteotest AG, 2017). In addition, Limassol, the second largest city of the island, is the hottest in the region with 221 Kdays. Moreover, Larnaca and Paphos having 340 Kdays and 223 Kdays respectively, represent the intermediate and the hot climate of the country.

3. Description of simulation software and algorithms, and data analysis

3.1. Simulation of the buildings' envelopes

The energy analysis of the building envelopes was conducted using the EnergyPlus simulation software which is appropriate for dynamically modelling the heating and cooling energy needs of buildings (DOE, 2017). For this purpose, 12 and 45 separate thermal zones were assigned to the single-family building and multi-family one, respectively. Following the inhabitants' common habits in the study area, the usage profiles of the interior spaces and the associated thermal comfort parameters were formulated on a daily, weekly and monthly base, considering continuous building operation all around the year. In addition, and in order to be more accurate and realistic, the daily usage profiles were divided into two separate periods. The first period starts at 07:00 and finalizes at 22:00, representing the high operation hours of the day. Moreover, a second low operation period, between 23:00 and 6:00, was considered, during which the cooling, heating, lighting and electrical equipment energy needs are substantially decreased. The

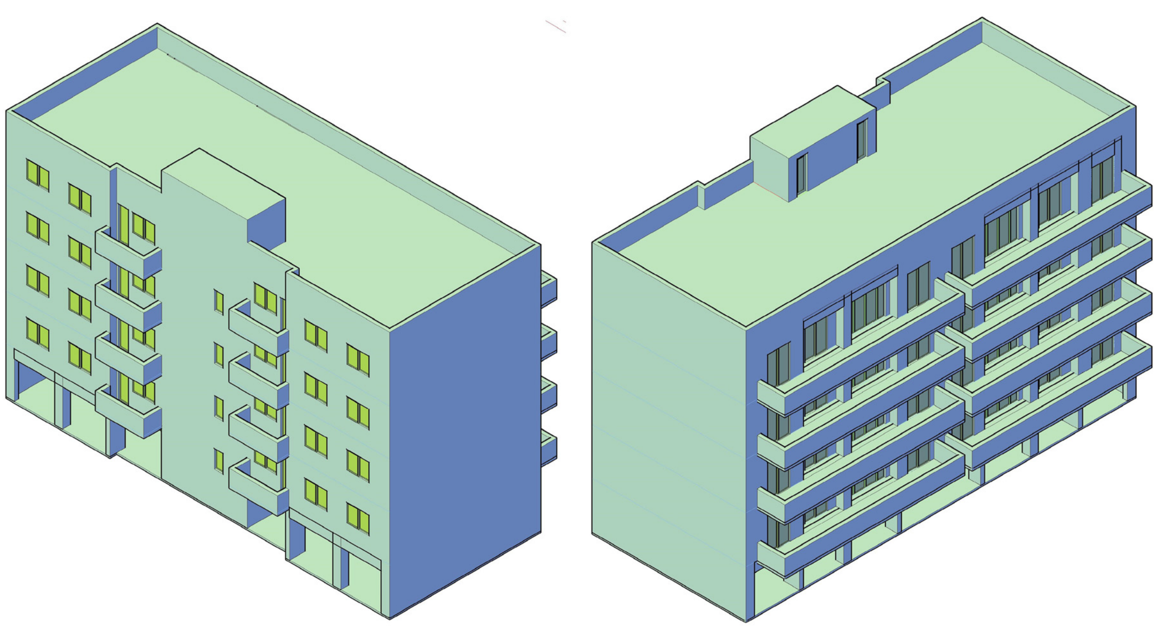

Fig. 2. Panoramic view of the examined multi-family building; South-West view *(a)* and North-West view *(b)*.

Table 1
EcoRoof Model parameters for both cases of selected plant cover (Ziogou et al., 2017).

			Helichrysum Orientale L. (Green Roof 1/GR1)		Sedum Sediforme (Green roof 2/GR2)	
Category	Field	Unit	Value	Reference	Value	Reference
Vegetation	Height of plants	m	0.15	Papafotiou et al. (2013)	0.25	Nektarios et al. (2014)
	Leaf area index	–	3.50	Varras et al. (2015)	1.75	Nektarios et al. (2014)
	Minimum stomatal resistance	s/m	125.00	Kokkinou et al. (2016)	300.00	Tabares-Velasco and Srebric (2012)
Growing medium	Thickness	m	0.075	Papafotiou et al. (2013)	0.15	Nektarios et al. (2014)
	Conductivity of dry soil	W/(m K)	0.20	Sailor, Hutchinson, and Bokovoy, (2008)	0.20	Sailor et al. (2008)
	Density of dry soil	kg/m^3	1020.00	Sailor et al. (2008)	1020.00	Sailor et al. (2008)
	Specific heat of dry soil	J/(kg K)	1093.00	Sailor et al. (2008)	1093.00	Sailor et al. (2008)
	Thermal absorptance	–	0.96	Sailor et al. (2008)	0.96	Sailor et al. (2008)
	Solar absorptance	–	0.85	Sailor et al. (2008)	0.83	Sailor et al. (2008)
	Saturation Volumetric Moisture Content of the Soil Layer	–	0.26	Sailor et al. (2008)	0.13	Sailor et al. (2008)
Irrigation	Irrigation Rate Schedule Name	l/h	3.30	Papafotiou et al. (2013); Van Mechelen, Dutoit and Hermy (2015)	*No irrigation*	Nektarios et al. (2014)

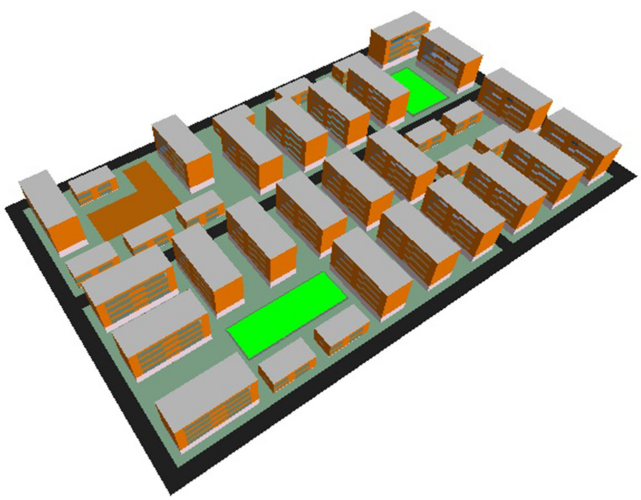

Fig. 3. 3D view of the examined residential area used in UHI analysis.

required temperature distribution during the high and low operation period for the heating and cooling process are set at 22 °C/18 °C and 25 °C/30 °C, respectively (ASHRAE, 2013; CEN, 2007). In addition, the daily rate of air changes is set at 0.8 ach (ASHRAE, 2013; CEN, 2007) and the lighting levels are equal to 6 W/m^2 (3.5 W/m^2 for WC) (ASHRAE, 2013; adapted from CEN, 2007).

The energy analysis of the green roofs was performed using again EnergyPlus software and more specifically the EcoRoof model that is incorporated in the program's simulation core. The parameters of the two alternative rooftop retrofit options' simulation are gathered in Table 1. The height of plants, the minimum stomatal resistance, the leaf area index, and the thickness of the substrate are major influencers regarding the green roofs' energy efficiency (Costanzo, Evola, & Marletta, 2016; Refahi & Talkhabi, 2015; Silva, Gomes, & Silva, 2016). Therefore, there are intentionally distinct differences in the values regarding the two alternative formations. Both cases of either the presence or the lack of irrigation of Helichrysum Orientale or Sedum Sediforme, respectively, rely on previously established experimental results that confirm the endurance of these species under extended dry periods (Nektarios et al., 2014; Papafotiou, Pergialioti, Tassoula, Massas, & Kargas, 2013). Last but not least, the required climatological data are extracted from the METEONORM's meteorological database.

3.2. Energy analysis of the heating and cooling system

The selected system for maintaining the required indoor conditions on heating and cooling period of the typical buildings took into consideration the recent market trends and customers' preferences on new and renovated dwellings. Based on that, a local heating and cooling system consisting of a variable speed split type air-to-air heat pump is considered in all cases. It is worth mentioning that although a local system is not favorable in terms of energy performance compared to the central one, it is selected in the frame of this study in order to simulate the existing construction practice of the study area.

The final energy consumption of the buildings' envelopes was calculated through a dynamic simulation procedure incorporated in an in-house developed model. More specifically, the buildings' heating and cooling energy demand, and the ambient air temperature were used as input parameters. Then, based on characteristic curves of the coefficient of performance or the energy efficiency ratio which were extracted from the engineering data book of the manufacturer (TOSHIBA, 2017) and are dependent on the hourly values of the ambient air temperature and the heat pump's load, the electricity consumption of the equipment was calculated.

3.3. Environmental analysis of the alternative rooftop retrofit options

For a quantitative comparison between the conventional individual buildings and the alternative ones with extensive green roofs with regard to their environmental impact, the emissions of CO_2, NO_x and SO_2 were calculated. To achieve this, the electricity consumption, resulting from the energy analysis of the heating and cooling system, was transformed into primary energy consumption, using the established national conversion factor that is equal to 2.7 kWh_{pr}/kWh_{el} (Republic of Cyprus, 2015a). Consequently, carbon dioxide emissions were calculated using the primary energy consumption through the established CO_2 emission factor (0.794) that is highly indicative of the fuel mix used in the national electricity production and provides the kilograms of released CO_2 per kWh of consumed primary energy (Republic of Cyprus, 2015a).

The emissions of the remaining local pollutants, i.e. NO_x and SO_2, are associated with the electricity produced in Cyprus according to Zachariadis and Hadjikyriakou (2016). Based on their analysis, the emission factors of the first and second pollutant are 1.29 and 3.94 tons of NO_x and SO_2 per GWh of the electricity production of power plants, respectively. The electricity consumption of the typical buildings that resulted from the analysis of the heating and cooling system was firstly converted to equivalent electricity production of the power plants by assuming transmission and distribution losses of 10.6% in line with recent evidence (EAC, 2015). Then, using the equivalent electricity production of power plants and the aforementioned emission factors, the emissions of these local pollutants were calculated on an annual basis.

3.4. Economic analysis of the alternative rooftop retrofit options

3.4.1. Economic feasibility

The economic evaluation of the extensive green roof solutions was performed using the Life Cycle Cost Analysis (LCCA) index, considering an economic lifespan of 30 years (EC, 2012). To address the social perspective, the analysis includes an assessment of changes in economic welfare due to the avoided environmental deterioration. Therefore, not only the operational costs but also the environmental costs of the emissions were incorporated in the calculation of the alternative rooftop retrofit options' Life Cycle Cost (LCC), as shown in the following equation.

$$LCC = -C_{in} - \sum_{j=1}^{n} \frac{EC \cdot C_{el,j}}{(1+d)^j} - \sum_{j=1}^{n} \frac{WC \cdot C_{w,j}}{(1+d)^j} - \sum_{j=1}^{n} \frac{C_{m,j}}{(1+d)^j} - \sum_{j=1}^{n} \frac{E_{CO_2} \cdot C_{CO_2,j}}{(1+d)^j} - \sum_{j=1}^{n} \frac{E_{SO_2} \cdot C_{SO_2,j}}{(1+d)^j} - \sum_{j=1}^{n} \frac{E_{NO_x} \cdot C_{NO_x,j}}{(1+d)^j}$$

C_{in} stands for the initial construction cost of the green roofs [€]. *EC* is the electricity consumption per year of the selected heating/cooling system [kWh_{el}/a] and $C_{el}j$ is the electricity cost for the *j*-year [€/kWh_{el}]. *WC* is the water consumption per year of the green roof system for irrigation purposes [m^3/a] and $C_{w}j$ is the water cost for the *j*-year [€/m^3]. $C_{m,j}$ represents the cost of maintenance works in *j*-year [€/a]. Moreover, E_{CO_2}, E_{SO_2}, and E_{NO_x} stand for the annual emissions of the indicated substances [kg/a], respectively, and $C_{CO_2,j}$, $C_{SO_2,j}$, and $C_{NO_x,j}$ refer to the annual cost per mass of emitted substances [€/kg], respectively. Finally, *d* is the discount rate [%] that reflects the social perspective, and *j* represents the calculation's year.

According to the information provided by the private company kartECO, the installation costs of the green roofs were estimated at the level of 8,330 € and 18,700 €, as of January 2017, for the single-family and multi-family building, respectively. Moreover, the maintenance cost was set equal to 3.5% of the installation cost, considering reasonable local present and forthcoming market prices. In addition, for the calculation of the yearly electricity cost, projections of the Energy Ministry of Cyprus of March 2017 were used for the 30-year period up to 2046.[1] Finally, the environmental costs per emission weight were extracted from the existing literature and appropriately adjusted to the economic conditions of Cyprus, as explained by Zachariadis and Hadjikyriakou (2016). All values are given at constant prices of year 2015. A social real discount rate of 4% was used, according to guidance provided to the government of Cyprus by the World Bank (World Bank, 2016) and in line with the broader relevant literature (Steinbach & Staniaszek, 2015), since the assessment focuses on the social perspective rather than the individual preferences of private investors.

3.4.2. Sensitivity analysis

In order to investigate the sensitivity of these calculations to the most uncertain parameters, we recalculated the LCCs of the extensive green roof systems assuming a range of possible investment costs and different future electricity costs. More specifically, we allowed the above-mentioned installation cost of 8330 € and 18,700 € for the single-family and multi-family building respectively, to decrease by up to 40%, assuming cost improvements due to technological progress or learning-by-doing as the number of such installations increases in the future.

As regards electricity costs, apart from the baseline price scenario that is used in the calculations described in Section 3.4.1, we assumed two additional scenarios reflecting a higher and a lower trajectory of electricity prices in the future. The low price scenario follows an unpublished "Reference" forecast of the Energy Ministry of Cyprus (see footnote 1), while the high price scenario follows the trend of the "Current Policies Scenario" from the latest World Energy Outlook of the International Energy Agency (IEA, 2016).

In short, while the baseline price scenario assumes retail electricity prices to remain close to today's levels and essentially constant in real terms (around 18 Eurocents'2015/kWh) up to the mid-2040s, the low price scenario assumes real electricity prices to fall slightly to 16–17 Eurocents'2015/kWh due to the introduction of natural gas in the power system of Cyprus; and according to the high price scenario, which assumes higher international oil and gas prices, retail electricity prices rise gradually up to 22 Eurocents'2015/kWh in the mid-2040s.

3.5. Simulation at the neighborhood scale

The environmental analysis for the selected residential neighborhood was conducted using ENVI-met software (version 4.3.0), an integrated three-dimensional non-hydrostatic model, simulating the interactions between natural and artificial surfaces, vegetation, and air layers (ENVI_MET GmbH, 2017b). The model calculations indicatively involve shortwave and longwave radiation interactions with vertical, horizontal and declined building components and urban vegetation, as well as the evapotranspiration and thermal procedures of plants considering all their physical parameters including photosynthesis rates, with the common calculation time ranging from 24 to 48 h (ENVI_MET GmbH, 2017b).

Earlier studies have already used this software in order to investigate the improvement potential of urban microclimatic conditions and have confirmed its reliability. The validity of the ENVI-met model has been proven through the high correlation between simulated data and measured ones (Berardi, 2016), low percentage deviation among the recorded and the simulated ambient temperature and humidity ratios (Battista, Carnielo, & De Lieto Vollaro, 2016), and low root mean square error values between the ENVI-met modelled and the experimentally observed air temperature (Jamei & Rajagopalan, 2017). The configuration details of the three-dimensional geometrical model along with the simulation parameters used in our analysis are presented in Table 2.

4. Results and discussion

4.1. Energy assessment

The primary energy consumption index (kWh/m^2) was herein utilized since it is a widely accepted energy efficiency indicator. The corresponding values during the heating and cooling operation and the percentage differences among the selected conventional flat roof and the corresponding alternative extensive green ones, for both insulated and uninsulated buildings, are provided in Figs. 4–7.

What stands out in the figures is that the highest reduction in primary energy consumption for heating purposes (almost 30%) is achieved by the extensive green roof configuration with the second vegetation covering for both types of buildings and insulation's application. On the contrary, the highest energy savings under the summer operation of the examined building types are accomplished when the extensive green roof configuration with the first plant option is applied, with energy savings well over 35% and 25% for the single-family and multi-family buildings respectively.

Regarding the uninsulated single-family buildings, the highest overall primary energy savings for heating and cooling (equal to 29%) are observed in the case of Nicosia which is the coldest region. A lower reduction – hardly exceeding 23% – is achieved in the remaining cities. In the insulated cases of single-family buildings, the overall primary energy reduction for heating and cooling is almost stable at 30%–32%. These results apply to both types of alternative rooftop retrofit options.

With regard to multi-family buildings and for all cities under

[1] This is an unpublished forecast made by energy authorities assuming that no natural gas will be used in power plants in the future ("No gas scenario"); it was obtained through personal communication with the Energy Ministry of Cyprus.

Table 2
ENVI-met model parameters.

Field	Value	Explanatory comment
Main model area	79 × 48 × 30	Number of grids
Grid size	2.50 m × 2.50 m × 1.00 m	Sufficient spatial resolution
Nesting grids around main area	3	In order to avoid boundary effects
Start simulation day	21/07/2017	Hottest day of the year for the selected location
Start simulation time	06:00	In order for the calculations to be in line with the atmospheric procedures
Total simulation hours	24 h	Minimum required duration is 6 h in order to prevent undesired effects (possibly caused by the transitory conditions in the initialization phase of the simulation) (ENVI_MET GmbH, 2017a)
Wind speed in 10 m above ground	1.32	Average value
Wind direction	189.89	The rotation of the modelled area (26.56° to the right) has been taken under consideration
Roughness Length z0 at Reference Point	0.01	Urban environment
Meteorology inputs	Temperature and relative humidity	Simple forcing was used and the data were extracted from the METEONORM weather files
Adjustment factor for shortwave solar radiation	0.82	Solar energy fluxes estimated by the internal method of ENVI-met are higher than the ones given by the METONORM weather files
Building and green roof properties	Similar to the ones used in EnergyPlus simulations	

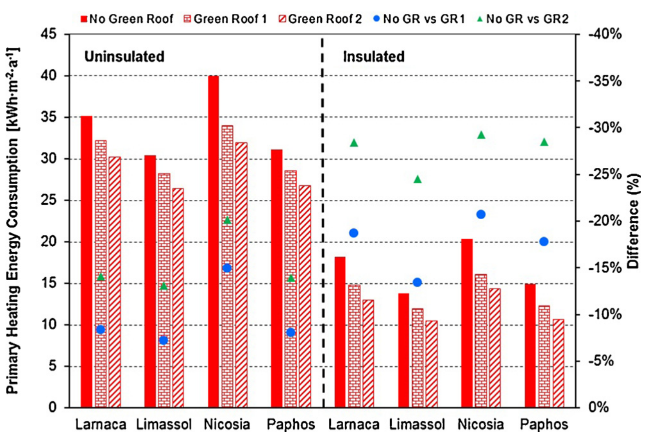

Fig. 4. Primary energy consumption of the single-family building during the heating period.

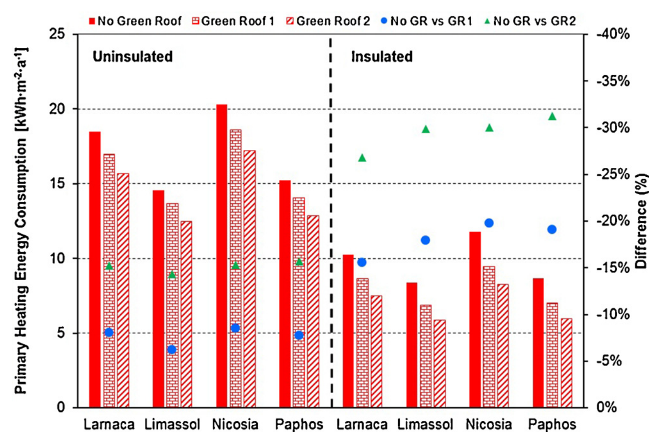

Fig. 6. Primary energy consumption of the multi-family building during the cooling period.

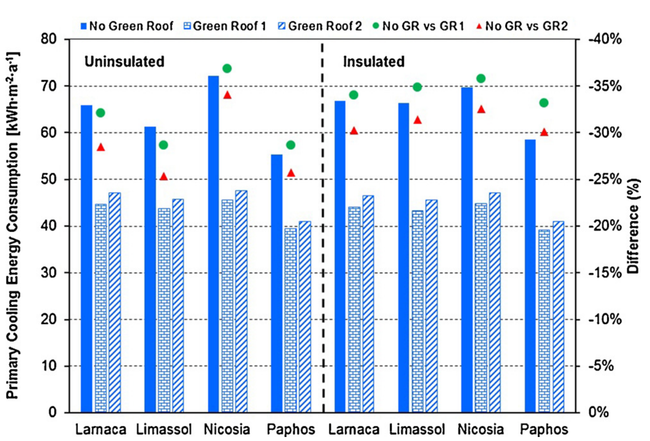

Fig. 5. Primary energy consumption of the single-family building during the cooling period.

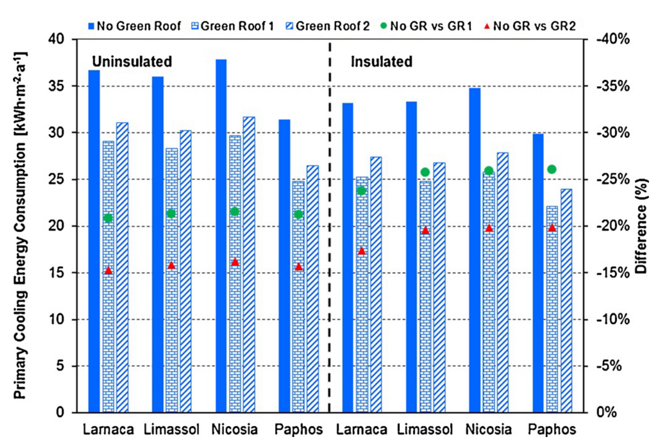

Fig. 7. Primary energy consumption of the multi-family building during the cooling period.

consideration, the extensive green roof with the first plant alternative offers the highest overall primary energy savings for heating and cooling of the order of 18% and 24% for uninsulated and insulated buildings, respectively. The corresponding reductions in the extensive green roof with the second vegetation type are 16% and 21% respectively. It is worth mentioning that the calculated energy savings are consistent among the different regions despite differences in their climatic characteristics.

4.2. Environmental evaluation

The ultimately reduced amounts of CO_2 emissions are presented in Figs. 8 and 9. It is apparent from these figures that a similar significant annual reduction of the emitted amounts of CO_2 is achieved, when either of the two types of extensive green roofs is applied. This positive impact is more profound both in single-and multi-family building for the case of perimetrically applied insulation.

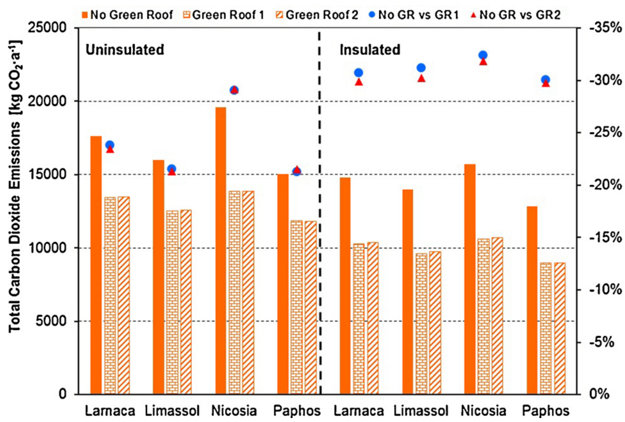

Fig. 8. Total CO_2 emissions produced under the annual operation of the single-family building.

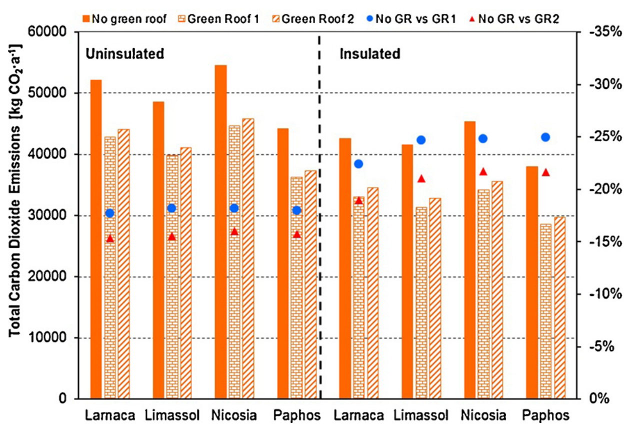

Fig. 9. Total CO_2 emissions produced under the annual operation of the multi-family building.

Fig. 10. Total NO_x emissions produced under the annual operation of the single-family building.

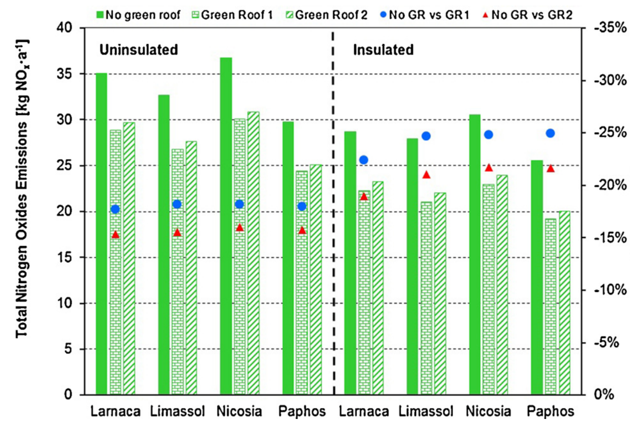

Fig. 11. Total NO_x emissions produced under the annual operation of the multi-family building.

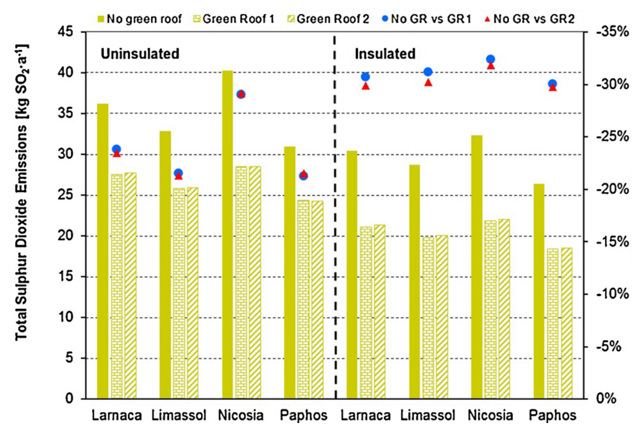

Fig. 12. Total SO_2 emissions produced under the annual operation of the single-family building.

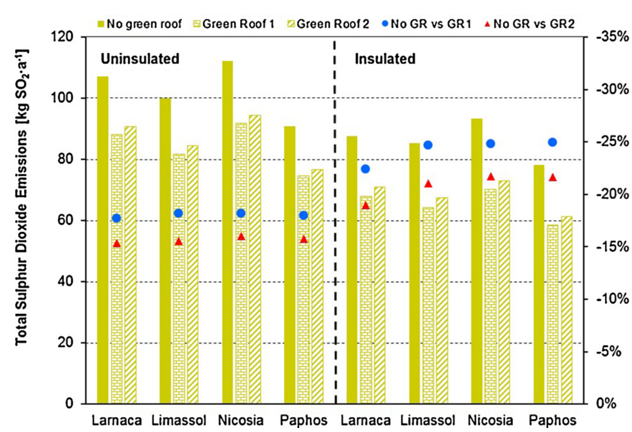

Fig. 13. Total SO_2 emissions produced under the annual operation of the multi-family building.

The indirect annual emissions of the remaining local pollutants are illustrated in Figs. 10–13.

The overall findings indicate that there is indeed an important reduction in NO_x and SO_2 emissions, regardless of the city in which either of the two extensive green roof configurations is applied. This reduction is stronger in single-family buildings. Both extensive green roof formations that are installed in single-family buildings seem to have a similar ameliorating impact on these local pollutant emissions, whereas in multi-family ones the first solution is environmentally more favorable (by roughly 2.4% and 3.3% in uninsulated and insulated cases respectively). The beneficial environmental impact of retrofitted roofs is more intensive in insulated buildings.

Still in absolute terms and compared to CO_2 emissions, emissions of local pollutants are relatively low. This figure can be attributed to the fuel mix in the electricity production in Cyprus (fuel oil, gas oil and renewable sources). The environmental improvements would clearly be higher in another country with a differentiated fuel mix (e.g. using coal-fired power plants), which would result in a more favorable evaluation of green roof technology.

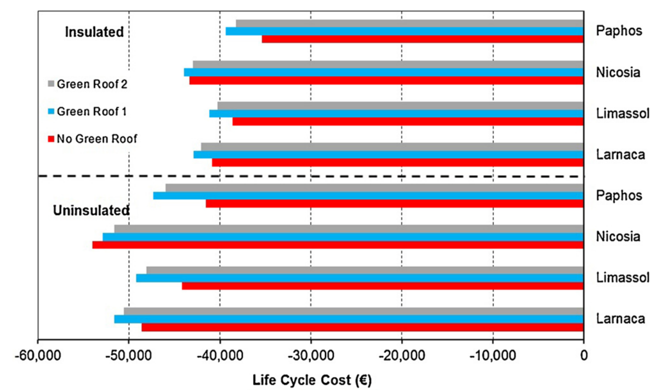

Fig. 14. Life Cycle Cost of conventional and retrofitted roofs of single-family buildings for an economic lifetime of 30 years.

4.3. Economic feasibility and sensitivity analysis

4.3.1. Economic feasibility

The resulting LCCs of the economic assessment are shown in Figs. 14 and 15. It appears that they are quite higher (in absolute terms) than the ones of the conventional flat-roof residential buildings, especially in the case of the single-family building, where the increased additional cost of a green roof seems to be discouraging for such an investment (see also Tapsuwan et al., 2018). An exception occurs for the city of Nicosia, where the proposed extensive green roof formations can provide a slight economic advantage, in the case of single-family buildings. Nevertheless, the general unfavorable trend could be reversed, if additional benefits, whose positive monetary contribution is hard to measure, were included in the economic analysis. These are conservation of local biodiversity (Bianchini & Hewage, 2012), added property value due to the enhancement of the aesthetic quality (Lee et al., 2014), reduction of urban noise levels (Connelly & Hodgson, 2015) and protection against urban flooding thanks to the increased storm water retention capacity of the green roofs (Volder & Dvorak, 2014).

4.3.2. Sensitivity analysis

As can be seen from Fig. 15, the second extensive green roof (Sedum Sediforme plantation) presents the lowest LCC compared to its alternative, in the case of multi-family buildings. In addition, Paphos and Nicosia are the locations with the lowest and highest economic efficiency of green roofs, respectively, in terms of the difference between the LCCs of "Green Roof 2" and "No Green Roof" scenarios. Figs. 16 and 17 show the results of this sensitivity analysis regarding the extensive green roof system with the second plant option in the cities of Nicosia and Paphos, for uninsulated and insulated multi-family buildings respectively. A positive value on the y-axis indicates that the LCC of the

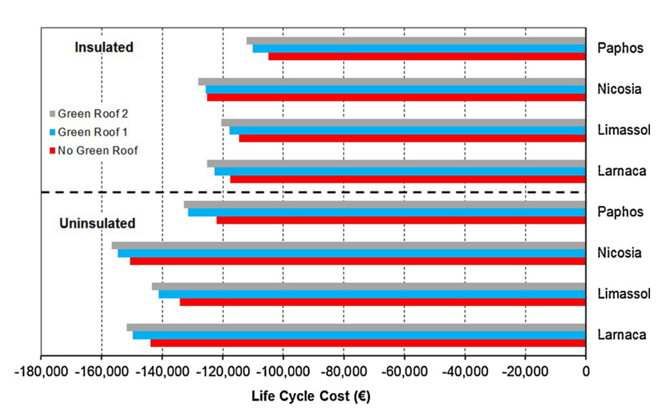

Fig. 15. Life Cycle Cost of conventional and retrofitted roofs of multi-family buildings for an economic lifetime of 30 years.

green roof system is greater than the LCC of the conventional building without green roof; in these cases, the building with green roof is financially more attractive than the conventional one. Evidently this comparison becomes more favorable for green roofs at higher electricity prices (which increases electricity cost savings) and lower green roof installation costs.

In the case of the most favorable location of Nicosia, modest improvements in investment costs, of the order of 6–22%, are sufficient for the green roof configuration to break even financially with the building without green roof. Adding the non-monetized benefits mentioned in Section 4.3.1, this would yield a clearly favorable comparison for the green roof systems. However, even higher reduction rates than the ones already selected in the installation cost of the green roof are required for the investment to be cost-effective in the less favorable area of Paphos. Moreover, the improvement of the economic feasibility of the two alternative rooftop retrofit options on the non-illustrated areas of Limassol and Larnaca lies in between the aforementioned figures.

Similar results, yet slightly improved, were obtained from the sensitivity analysis of the extensive green roof with the first plant option in the multi-family building in all examined areas and under all the examined electricity price scenarios. With respect to single-family buildings and for the most disadvantageous city of Paphos, decreased investment costs varying from 18% up to 35% can turn the two proposed retrofit options into economically viable solutions. These results are not reported here for the sake of brevity but are available in the supplementary file accompanying this paper. Again, one has to keep in mind the non-monetized benefits of green roofs that were mentioned in the previous section, which can substantially change the overall LCC result.

4.4. Impact on urban microclimatic conditions

The analysis has focused on air temperature differences at the pedestrian level on the neighborhood scale. Based on the percentage differences in the primary energy consumption between the flat roof buildings and the ones with green roofs, the location of Limassol and the case of perimetrically insulated residential buildings have been selected. Figs. 18 and 19 present the spatial distribution of the numerical differences in air temperature between the base case scenario and the two alternative rooftop retrofit options (aromatic xerophyte and succulent plant) during the hottest hour of the summer design day.

As can be seen from the figures above, the first type of the examined extensive green roofs yields more positive results since the cooling effect is 0.1 K higher than the one offered by the second type, following the same trend with the reduction in primary energy consumption of individual buildings as described in Section 4.1. Generally, the decrease in air temperature at the selected height is apparent and starts to appear from the middle part up to the top right side of the examined area in consistence with the air direction.

Nevertheless, one should keep in mind that roof surface covers only about 20% of the entire urban surfaces; hence applying greenery in the remaining surface is highly recommended for stronger UHI mitigation (Morakinyo et al., 2017). In addition, expanded application of green roofs at an even larger (e.g. district or city) scale would certainly have a clearer effect on the improvement of the urban micro-climate (Berardi, 2016).

5. Conclusions

This study has thoroughly evaluated two alternative rooftop retrofit options (i.e. extensive green roofs with two different native plant solutions) for two dominant types of residential buildings in Cyprus. We have thus provided a comprehensive energy, environmental and economic analysis of these passive building design solutions combined with the examination of their contribution to the upgrade of urban micro-climatic conditions. The results of this study can be considered representative for the majority of Mediterranean areas since climatic

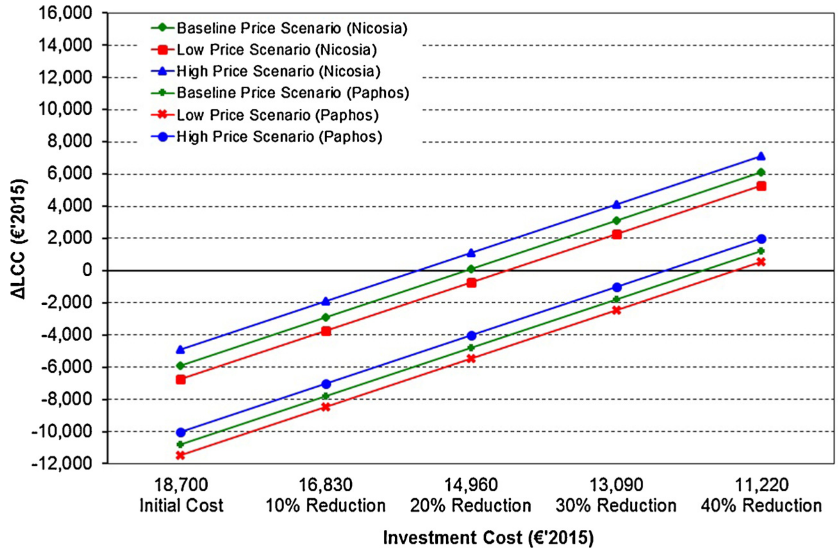

Fig. 16. Sensitivity analysis of the extensive green roof system with the second plant option (Sedum Sediforme) for the uninsulated multi-family building in Nicosia and Paphos.

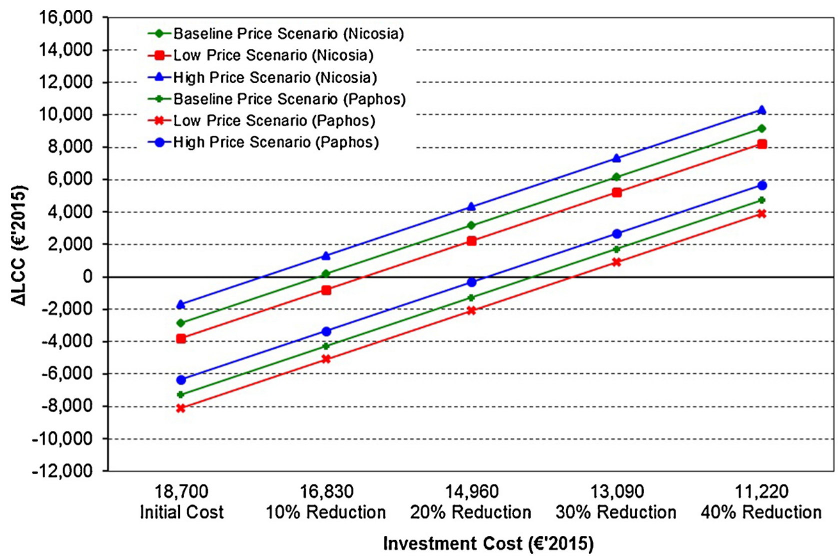

Fig. 17. Sensitivity analysis of the extensive green roof system with the second plant option (Sedum Sediforme) for the insulated multi-family building in Nicosia and Paphos.

characteristics, building regulations, and urban planning conditions in the region are broadly similar with the ones prevailing in Cyprus.

We have confirmed the clearly positive energy and environmental contribution of green roofs. Indicatively, primary energy savings on heating mode can reach 30% for both building typologies, while under summer operation 35% and 25% reductions in primary energy consumption are found, for the considered single-family and multi-family buildings, respectively. The same reduction pattern applies to the indirect CO_2, NO_x, and SO_2 emissions. Regarding the economic aspects, our analysis has indicated that such an investment in the residential sector is, in most cases, still not cost-efficient, because of the high installation cost. However, sensitivity analysis has demonstrated that green roofs become economically viable with only modest reductions (varying from 6% to 35%) in their installation cost, which are possible in the medium term because of technological progress or learning-by-doing due to their increased deployment. This prospect can be encouraging for local homeowners or real estate developers to eventually include green roofs in their preferable building's envelope upgrades.

Additionally, one should keep in mind that there are added associated environmental gains which are currently hard to quantify financially. In addition, following the results of our environmental simulations, the consideration of broadly applying green roofs at a wider urban scale can indeed upgrade the micro-climatic conditions of even spatially constrained urban areas, such as local neighborhoods. As a result, the resilience of urban communities against deterioration of climatic conditions can be enhanced – thus offering further environmental and economic advantages. Competent authorities should carefully consider this perspective in their efforts towards planning and applying green urban construction and renovation projects.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Acknowledgments

The authors would like to express their appreciation to the editor

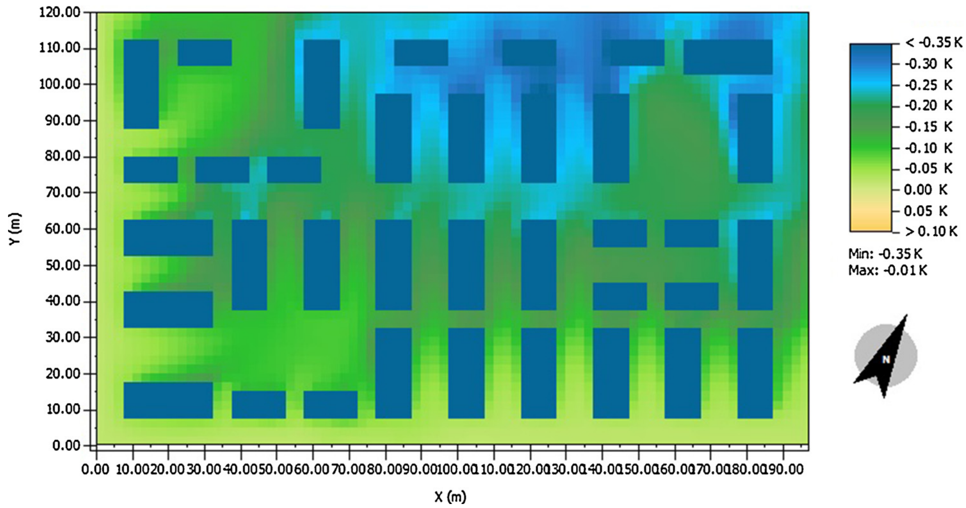

Fig. 18. Numerical difference in air temperature between the conventional and first extensive green roof (Helichrysum Orientale) scenarios at z = 1.50 m for the 21st of July at 16:00 pm.

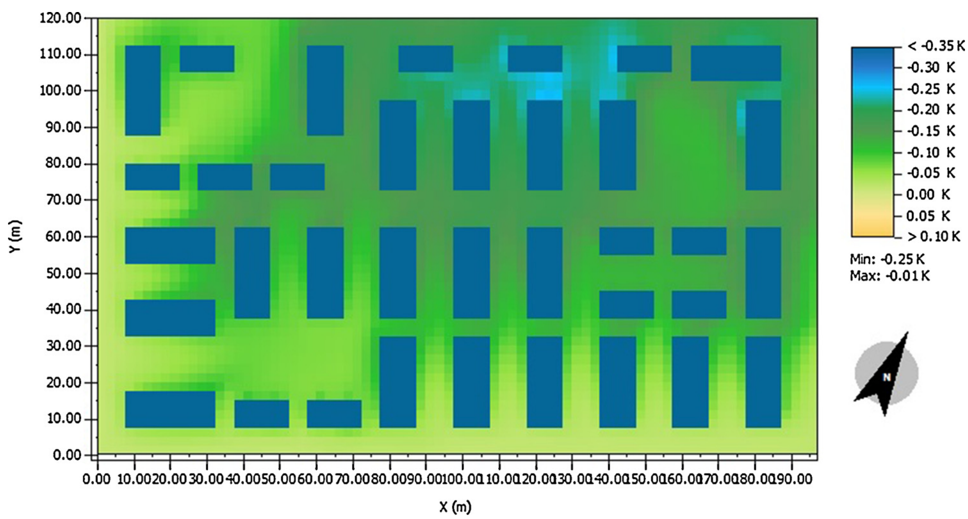

Fig. 19. Numerical difference in air temperature between the conventional and second extensive green roof (Sedum Sediforme) scenarios at z = 1.50 m for the 21st of July at 16:00 pm.

and two anonymous reviewers, for their insightful comments and constructive suggestions.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.scs.2018.04.007.

References

ASHRAE (2013). *ASHRAE handbook: Fundamentals.* American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Alcazar, S. S., Olivieri, F., & Neila, J. (2016). Green roofs: Experimental and analytical study of its potential for urban microclimate regulation in Mediterranean?continental climates. *Urban Climate, 17*, 304–317. http://dx.doi.org/10.1016/j.uclim.2016.02.004.

Battista, G., Carnielo, E., & De Lieto Vollaro, R. (2016). Thermal impact of a redeveloped area on localized urban microclimate: A case study in Rome. *Energy and Buildings, 133*, 446–454. http://dx.doi.org/10.1016/j.enbuild.2016.10.004.

Berardi, U., GhaffarianHoseini, A., & GhaffarianHoseini, A. (2014). State-of-the-art analysis of the environmental benefits of green roofs. *Applied Energy, 115*, 411–428. http://dx.doi.org/10.1016/j.apenergy.2013.10.047.

Berardi, U. (2016). The outdoor microclimate benefits and energy saving resulting from green roofs retrofits. *Energy and Buildings, 121*, 217–229. http://dx.doi.org/10.1016/j.enbuild.2016.03.021.

Bianchini, F., & Hewage, K. (2012). How green are the green roofs? Lifecycle analysis of green roof materials. *Building and Environment, 48*(1), 57–65. http://dx.doi.org/10.1016/j.buildenv.2011.08.019.

Butler, C., Butler, E., & Orians, C. M. (2012). Native plant enthusiasm reaches new heights: Perceptions, evidence, and the future of green roofs. *Urban Forestry and Urban Greening, 11*(1), 1–10. http://dx.doi.org/10.1016/j.ufug.2011.11.002.

CEN (2007). *EN 15251:2007 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.* European Committee for Standardization.

CYSTAT (2015). *Construction and housing statistics. Printing office of the republic of Cyprus.* Cyprus Statistical Service [Retrieved from http://www.mof.gov.cy/mof/cystat/statistics.nsf/industry_construction_62main_en/industry_construction_62main_en?OpenForm&sub = 2&sel = 4].

Connelly, M., & Hodgson, M. (2015). Experimental investigation of the sound absorption characteristics of vegetated roofs. *Building and Environment, 92*, 335–346. http://dx.doi.org/10.1016/j.buildenv.2015.04.023.

Costanzo, V., Evola, G., & Marletta, L. (2016). Energy savings in buildings or UHI mitigation? Comparison between green roofs and cool roofs. *Energy and Buildings, 114*, 247–255. http://dx.doi.org/10.1016/j.enbuild.2015.04.053.

DOE (2017). *Department of energy; US.* EnergyPlus [Retrieved June 14, 2017, from https://energyplus.net].

EAC (2015). *Annual report 2015*Electricity Authority of Cyprus [Retrieved from https://www.eac.com.cy/EN/EAC/FinancialInformation/Documents/Annual Report-English 2015-FINAL.pdf].

EC (2012). *COMMISSION DELEGATED REGULATION (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology framework for calculating.* European Commission.

ENVI_MET GmbH (2017a). *ENVI-met basic settings.* [Retrieved March 24, 2018, from http://envi-met.info/doku.php?id = basic_settings&s = simulation&s = time].

ENVI_MET GmbH (2017b). *ENVI-met model architecture.* [Retrieved March 24, 2018, from http://envi-met.info/doku.php?id=intro:modelconcept].

Goussous, J., Siam, H., & Alzoubi, H. (2015). Prospects of green roof technology for energy and thermal benefits in buildings: Case of Jordan. *Sustainable Cities and Society, 14*(1), 425–440. http://dx.doi.org/10.1016/j.scs.2014.05.012.

Hill, J., Drake, J., & Sleep, B. (2016). Comparisons of extensive green roof media in Southern Ontario. *Ecological Engineering, 94*, 418–426. http://dx.doi.org/10.1016/j.ecoleng.2016.05.045.

IEA (2016). *World energy outlook 978-92-64-26495-3.* Paris, France: International Energy Agency.

IPCC (2014). In Core Writing Team, R. K. Pachauri, & L. A. Meyer (Eds.). *Climate change 2014: Synthesis report. contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change* (pp. 151). Geneva, Switzerland: Intergovernmental Panel on Climate Change.

Jamei, E., & Rajagopalan, P. (2017). Urban development and pedestrian thermal comfort in Melbourne. *Solar Energy, 144*, 681–698. http://dx.doi.org/10.1016/j.solener.2017.01.023.

Jim, C. Y. (2014). Air-conditioning energy consumption due to green roofs with different building thermal insulation. *Applied Energy, 128*, 49–59. http://dx.doi.org/10.1016/j.apenergy.2014.04.055.

Jim, C. Y. (2015). Diurnal and partitioned heat-flux patterns of coupled green-building roof systems. *Renewable Energy, 81*, 262–274. http://dx.doi.org/10.1016/j.renene.2015.03.044.

Jim, C. Y. (2017). Green roof evolution through exemplars: Germinal prototypes to modern variants. *Sustainable Cities and Society, 35*(June), 69–82. http://dx.doi.org/10.1016/j.scs.2017.08.001.

Kokkinou, I., Ntoulas, N., Nektarios, P. A., & Varela, D. (2016). Response of native aromatic and medicinal plant species to water stress on adaptive green roof systems. *HortScience, 51*(5), 608–614.

Lee, K. E., Williams, K. J. H., Sargent, L. D., Farrell, C., & Williams, N. S. (2014). Living roof preference is influenced by plant characteristics and diversity. *Landscape and Urban Planning, 122*, 152–159. http://dx.doi.org/10.1016/j.landurbplan.2013.09.011.

Meteotest AG (2017). *METEONORM.* [Retrieved March 8, 2018, from http://www.meteonorm.com/en].

Morakinyo, T. E., Kalani, K. W. D., Dahanayake, C., Ng, E., & Chow, C. L. (2017). Temperature and cooling demand reduction by green-roof types in different climates and urban densities: A co-simulation parametric study. *Energy and Buildings, 145*, 226–237. http://dx.doi.org/10.1016/j.enbuild.2017.03.066.

Nektarios, P. A., Ntoulas, N., Nydrioti, E., Kokkinou, I., Bali, E. M., & Amountzias, I. (2014). Drought stress response of Sedum sediforme grown in extensive green roof systems with different substrate types and depths. *Scientia Horticulturae, 181*, 52–61. http://dx.doi.org/10.1016/j.scienta.2014.10.047.

Pérez, G., Vila, A., Rincón, L., Solé, C., & Cabeza, L. F. (2012). Use of rubber crumbs as drainage layer in green roofs as potential energy improvement material. *Applied Energy, 97*, 347–354. http://dx.doi.org/10.1016/j.apenergy.2011.11.051.

Pandey, S., Hindoliya, D. A., & Mod, R. (2012). Artificial neural network for predation of cooling load reduction using green roof over building in sustainable city. *Sustainable Cities and Society, 3*(1), 37–45. http://dx.doi.org/10.1016/j.scs.2012.01.003.

Papafotiou, M., Pergialioti, N., Tassoula, L., Massas, I., & Kargas, G. (2013). Growth of native aromatic xerophytes in an extensive Mediterranean green roof as affected by substrate type and depth and irrigation frequency. *HortScience, 48*(10), 1327–1333.

Refahi, A. H., & Talkhabi, H. (2015). Investigating the effective factors on the reduction of energy consumption in residential buildings with green roofs. *Renewable Energy, 80*, 595–603. http://dx.doi.org/10.1016/j.renene.2015.02.030.

Republic of Cyprus Department of Meteorology (2017). *The climate of Cyprus.* [Retrieved June 13, 2017, from http://www.moa.gov.cy/moa/ms/ms.nsf/DMLcyclimate_en/DMLcyclimate_en?OpenDocument].

Republic of Cyprus (2015a). *Decree 33/2015, Law regulating the energy performance of buildings, Methodology for calculating the energy performance of a building.* [(in Greek), Retrieved from http://www.mcit.gov.cy/mcit/mcit.nsf/All/DF8E187B6AF21A89C22575AD002C6160/$file/Κ.Δ.Π.33-2015_Περί Ρυθμισης της Ενεργειακης Αποδοσης (Μεθοδολογια).pdf].

Republic of Cyprus (2015b). *Decree 359/2015, Law regulating the energy performance of buildings.* [(in Greek), Retrieved from http://www.mcit.gov.cy/mcit/mcit.nsf/0/DF8E187B6AF21A89C22575AD002C6160/$file/KDP359_2015_KDP3_2016 Peri Rithmisis Energ Apod Ktir(Apaitiseis Elaxistis Energ Apodosis)Diat2015_2016.pdf].

Sailor, D. J., Hutchinson, D., & Bokovoy, L. (2008). Thermal property measurements for ecoroof soils common in the western U.S. *Energy and Buildings, 40*(7), 1246–1251. http://dx.doi.org/10.1016/j.enbuild.2007.11.004.

Silva, C. M., Gomes, M. G., & Silva, M. (2016). Green roofs energy performance in Mediterranean climate. *Energy and Buildings, 116*, 318–325. http://dx.doi.org/10.1016/j.enbuild.2016.01.012.

Steinbach, J., & Staniaszek, D. (2015). *Discount rates in energy system analysis. discussion paper, buildings performance institute europe and fraunhofer institute.* [May 2015, Retrieved from http://bpie.eu/uploads/lib/document/attachment/142/Discount_rates_in_energy_system-discussion_paper_2015_ISI_BPIE.pdf].

TOSHIBA (2017). *Engineering data book, TCTC-E15-RES002*.

Tabares-Velasco, P. C., & Srebric, J. (2012). A heat transfer model for assessment of plant based roofing systems in summer conditions. *Building and Environment, 49*(1), 310–323. http://dx.doi.org/10.1016/j.buildenv.2011.07.019.

Tapsuwan, S., Mathot, C., Walker, I., & Barnett, G. (2018). Preferences for sustainable, liveable and resilient neighbourhoods and homes: A case of Canberra, Australia. *Sustainable Cities and Society, 37*(October 2017), 133–145. http://dx.doi.org/10.1016/J.SCS.2017.10.034.

Theodosiou, T., Aravantinos, D., & Tsikaloudaki, K. (2014). Thermal behaviour of a green vs. a conventional roof under Mediterranean climate conditions. *International Journal of Sustainable Energy, 33*(1), 227–241. http://dx.doi.org/10.1080/14786451.2013.772616.

UN (2015). *World urbanization prospects: The 2014 revision, (ST/ESA/SER.A/366).* United Nations, Department of Economic and Social Affairs, Population Division.

Van Mechelen, C., Dutoit, T., & Hermy, M. (2015). Adapting green roof irrigation practices for a sustainable future: A review. *Sustainable Cities and Society, 19*, 74–90. http://dx.doi.org/10.1016/j.scs.2015.07.007.

Varras, G., Vozikis, K.-T., Myriounis, C., Tsirogiannis, I. L., & Kitta, E. (2015). Design of extensive green roofs for the major school plants of piraeus. *Acta Horticulturae, 1099*(1099), 959–966. http://dx.doi.org/10.17660/ActaHortic.2015.1099.122.

Vijayaraghavan, K. (2016). Green roofs: A critical review on the role of components, benefits, limitations and trends. *Renewable and Sustainable Energy Reviews, 57*, 740–752. http://dx.doi.org/10.1016/j.rser.2015.12.119.

Volder, A., & Dvorak, B. (2014). Event size, substrate water content and vegetation affect storm water retention efficiency of an un-irrigated extensive green roof system in Central Texas. *Sustainable Cities and Society, 10*, 59–64. http://dx.doi.org/10.1016/j.scs.2013.05.005.

Vuckovic, M., Kiesel, K., & Mahdavi, A. (2017). Studies in the assessment of vegetation impact in the urban context. *Energy and Buildings, 145*, 331–341. http://dx.doi.org/10.1016/j.enbuild.2017.04.003.

World Bank (2016). *Guidebook for the pre-selection and assessment of public investment projects.* World Bank Group [November 2016, in Greek].

Yang, W., Wang, Z., Cui, J., Zhu, Z., & Zhao, X. (2015). Comparative study of the thermal performance of the novel green (planting) roofs against other existing roofs. *Sustainable Cities and Society, 16*, 1–12. http://dx.doi.org/10.1016/j.scs.2015.01.002.

Zachariadis, T., & Hadjikyriakou, C. (2016). *Social costs and benefits of renewable electricity generation in Cyprus.* Cham: Springer International Publishinghttp://dx.doi.org/10.1007/978-3-319-31535-5.

Ziogou, I., Michopoulos, A., Voulgari, V., & Zachariadis, T. (2017). Energy, environmental and economic assessment of electricity savings from the operation of green roofs in urban office buildings of a warm Mediterranean region. *Journal of Cleaner Production, 168*, 346–356. http://dx.doi.org/10.1016/j.jclepro.2017.08.217.